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SOLID-STATE ULTRASONIC CATHETER-TIP FLOWMETER.(U)

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A blood flowmeter measures the difference in upstream and downstream transit times for short bursts of 10-MHz ultrasound with the two transducers required mounted in a catheter tip. This instrument can measure flow as small as 0.1 cm/s, with a response time of 5 ms. A method is proposed to measure the cross-sectional area of the vessel so that the volume flow rate and the flow velocity can be determined.

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FIGURES

FIGURES (Cont'd)

1. INTRODUCTION

The solid-state ultrasonic catheter-tip flowmeter is the same in principle as that described by Kalmus,[1] by Kalmus, Hedrich, and Pardue,[2] and later in a form suitable for catheter-tip transducer mounting by Pardue, Hedrich, Rose, and Kot.[3] The transmitting and receiving functions of two ultrasonic transducers are periodically interchanged so that the difference between upstream and downstream transit times of ultrasonic pulses can be measured in the blood vessels of an animal.

One advantage of a catheter-tip sensor over the "cuff" types frequently used with ultrasonic or electromagnetic flowmeters is the relatively minor surgery required for its installation. Another important advantage is the extreme stability of the acoustic path. The transducers are rigidly held in the tip so that no variations in path length or transducer orientation occur. The transmission medium consists entirely of fluid (blood) with constant acoustic properties; that is, no vessel wall with varying thickness or coupling efficiency need be penetrated by the ultrasound. Therefore, the signal amplitude is constant, and signal processing is simplified.

All circuits in this version are constructed with solid-state components in a package 4 × 10 × 20 cm. The combination of all improvements results in about one decade increase in sensitivity compared to instruments discussed elsewhere,[1,3] so that zero stability corresponds to a 0.1-cm/s flow velocity. The response time of 5 ms can be shortened if desirable, but is probably short enough for blood flow.

2. CATHETERS

The geometry of a catheter-tip probe in a large vessel is indicated in figure 1. A bend of about 25 deg is placed in the catheter body. It is assumed that the bend maintains the position of the tip both during the heartbeat and during the respiratory cycle if the tip has been inserted between the diaphragm and the aortic valve.

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[1] *Henry P. Kalmus, Electronic Flowmeter System, Rev. Sci. Instr. (March 1954).*

[2] *H. P. Kalmus, A. L. Hedrich, and D. R. Pardue, The Acoustic Flowmeter Using Electronic Switching, IRE Trans. Ultrason. Eng., PGUE-1 (1954), 49.*

[3] *D. R. Pardue, A. L. Hedrich, J. C. Rose, and P. H. Kot, Ultrasonic Catheter-Tip Probe for Measuring Blood Flow Velocity, IEEE Trans. Sonics Ultrason., SU-22 (March 1975), 2.*

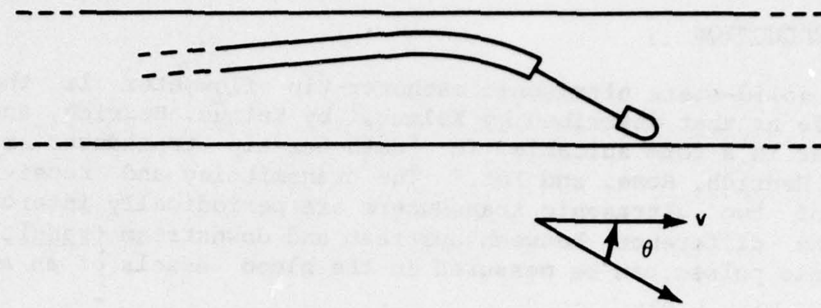

Figure 1. Catheter-tip probe at angle θ with respect to average flow.

An expanded cross section through the axis of symmetry for the tip is shown in figure 2. A hypodermic needle No. 22 contains the signal lead for the end transducer. Both signal leads are 0.013-in. (0.033 cm) microcoaxial or semirigid cable in the catheter body and up to the points indicated by black dots close to the transducer assemblies, where they are soldered to the transducer leads. The Dow-Corning silastic room-temperature vulcanizing (RTV) is used as shown in figure 2 both to electrically insulate the transducer electrodes and leads and to prevent acoustic coupling through the hypodermic needle. In this configuration, the transducers are completely surrounded by the RTV, and because the RTV is such a poor transmission medium, the received acoustic signal travels only through the blood.

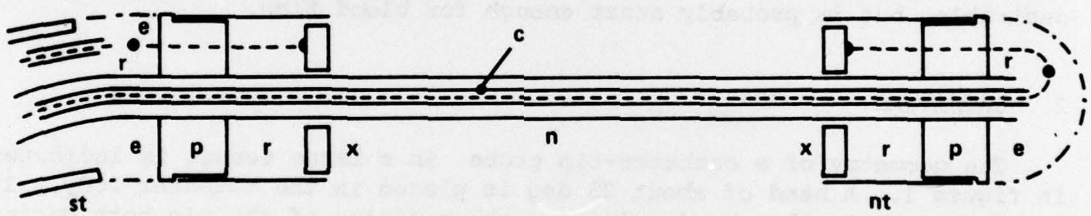

Figure 2. Construction of catheter tip (x: transducers, r: RTV filling, nt: nickel tubing, p: brass plugs, e: conducting epoxy, n: hypodermic needle, c: microcoaxial cable, and st: heat-shrinkable tubing).

The hypodermic needle extends for about 1 cm into the catheter body (not shown in fig. 2). A 0.010-in. (0.025-cm) piano wire is soldered to this needle to strengthen the catheter and still maintain adequate flexibility. At the other end, the outer conductors of two RG-174 cables are soldered to this piano wire. They have Selectro fittings for chassis connectors. The two microcoaxial-cable leads are then connected to these fittings and shielded so that no electrical coupling exists between them. Heat-shrinkable tubing is applied over the piano wire and the two microcoaxial cables; hence, the catheter body is smooth, and blood clots do not form on it.

This construction method for catheter tips gives much better control during assembly than do previous methods and makes it possible to control transducer alignment. The acoustic beam width is only 6 deg, so the outer transducer surfaces must be parallel to each other.

The assembly procedure for the tips is as follows:

a. The signal or inner transducer surfaces are covered uniformly and symmetrically with solder on a hot plate. Their surfaces are metalized with nickel, so flux No. 1 and solder No. 5 from the Indium Corp. of America's "Research Solder Kit" are used. (Flux No. 2 and solder No. 9 work for piano wire and hypodermic needles.) Then short 0.004-in. (0.01-cm) copper leads are attached.

b. The transducers are held to a smooth Teflon surface with a thin ring of RTV around the circumference, and the nickel tubes (0.090-in.--0.225-cm--o.d. with 0.002-in.--0.005-cm--wall thickness) are placed concentrically over them. More of these can be prepared than are required, and after the RTV vulcanizes, those not meeting geometrical requirements are reworked. Then a 0.001- to 0.002-in. (0.0025- to 0.005-cm) coating of RTV is applied to the surface of the transducer hole and allowed to vulcanize.

c. The left brass plug (fig. 2) is soldered to the hypodermic needle with flux No. 2 and solder No. 9.

d. A thin groove is cut in the edge of both brass plugs for the transducer leads.

e. A cone of RTV is applied to the hypodermic needle--more RTV than is required to fill the nickel tube. Then the tube-transducer assembly is pushed into position, and the excess RTV squeezes through the lead groove and the transducer hole. The RTV is then allowed to vulcanize before the nickel tube can be spot soldered to the brass plugs. (Fresh RTV boils out at soldering temperature and creates voids.)

f. The other tube-transducer assembly is placed on the needle with the transducers close together, the other plug is soldered, and the right assembly is finished like the left. The RTV in both cavities is then allowed to vulcanize.

g. Nickel tubes are spot soldered to the brass plugs.

h. The piano wire is soldered to the needle (flux No. 2 and solder No. 9). The outer conductor of one microcoaxial cable is soldered where it enters the needle; that of the other, to the outside of the needle.

i. Signal leads are connected to coaxial cable leads and insulated with the RTV.

j. Conducting epoxy is applied (fig. 2), Epo-Tek H-31, for example.

k. Ground connections (not shown in fig. 2) are made between the nickel tube and transducer by attaching a short 0.003-in. (0.0075-cm) copper wire with conducting epoxy.

l. After the conducting epoxy cures, a thin film of quick-drying cement (Aron Alpha by Toagosei Chemical Industry Co., Ltd.) is applied to give strength and also to prevent blood clots.

m. Cables with Selectro fittings are assembled: their outer conductors are soldered to the piano wire, and their inner conductors are joined to those from the microcoaxial cable. For insulation and shielding, 0.002-in (0.005-cm) brass shim stock is bent and soldered around each cable. Finally, the heat-shrinkable tubing is applied.

3. CIRCUITS

A block diagram of circuits is shown in figure 3. Video pulses about 75 ns long are supplied by the pulse generator at a 256-kHz repetition rate and drive the divider. Pulses of 1 kHz from the divider drive a bistable multivibrator, which supplies two 500-Hz out-of-phase square waves, A and B, which operate the switching amplifiers and the synchronous detector.

Each of the four switching amplifiers consists of two stages of dual-gate amplification by metal oxide semiconductor field effect transistors (MOSFET's). The first gate carries the signals, and the second gate switches the amplifiers on or off during alternate 1-ms intervals. Amplifiers 1 and 4 "on" and 2 and 3 "off" correspond to downstream propagation in the sound path; amplifiers 1 and 4 "on" and 2 and 3 "off" correspond to upstream propagation. The ratio of transmitted to received voltages on a tranducer is about 40 dB. The ratio of "on" to "off" gain in each switching amplifier is about 140 dB, so that electrical feedthrough is well below the signal level (100 dB). Also, the acoustic path length is chosen so that feedthrough and signal pulses are separated in time.

The phase detector is a bistable multivibrator with two inputs--(1) a reference input driven by pulses from the generator and (2) a signal input driven by amplified pulses from the acoustic path. The phase-detector output is a rectangular wave at 256 kHz, with symmetry

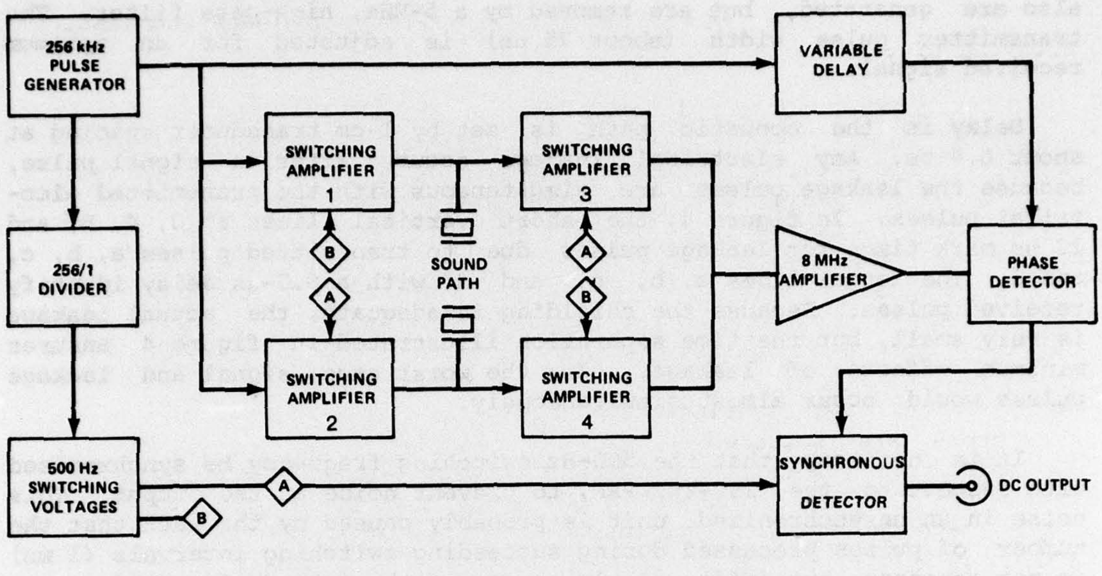

Figure 3. Flowmeter.

depending on the time relationship between the reference and the signal pulses. This relationship is adjusted by a variable delay in the reference channel to give approximately square waves on the phase detector at zero flow. As the flow increases, the symmetry of these waves changes in one direction for upstream propagation and in the other direction for downstream propagation. When the multivibrator signal is processed by a low-pass filter to remove the 256-kHz component, there remain a 500-Hz square wave with amplitude proportional to the flow and a phase of 0 or 180 deg with respect to the switching voltage generator, depending on the flow direction. The synchronous detector converts this square wave to dc, with magnitude proportional to flow and sign dependent on the flow direction. Thus, the voltage output is linear and reverses sign if flow reverses its direction. Calibration at moderate flow rates makes it possible to express a zero drift of the output voltage in terms of the flow rate, and this calibrated value corresponds to a minimum measurable flow.

Although the predominant frequencies transmitted acoustically are in a band centered around 10 MHz, the voltage applied to the transmitting transducer consists of a chain of narrow video pulses repeated at 4-μs intervals. The frequency response of the transducers operating in the thickness mode (0.010 in.--0.025 cm--thick) restricts the received signal to a band centered around 10 MHz. Two radial modes at 1 and 3 MHz

also are generated, but are removed by a 5-MHz, high-pass filter. The transmitter pulse width (about 75 ns) is adjusted for an optimum received signal.

Delay in the acoustic path is set by 1-cm transducer spacing at about 6.7 μs. Any electrical leakage occurs after a signal pulse, because the leakage pulses are simultaneous with the transmitted electrical pulses. In figure 4, the short vertical lines at 0, 4, 8, and 12 μs mark times for leakage pulses due to transmitted pulses a, b, c, and d. The longer lines a, b, c, and d with a 6.7-μs delay identify received pulses. Because the shielding is adequate, the actual leakage is very small, but the time separation illustrated in figure 4 ensures minimum effects of leakage. In the worst case, signal and leakage pulses would occur almost simultaneously.

It is necessary that the 500-Hz switching frequency be synchronized with respect to the 250-kHz PRF, to prevent noise at the output. This noise in an unsynchronized unit is probably caused by the fact that the number of pulses processed during succeeding switching intervals (1 ms) is not constant, but drifts slowly as one of the frequencies varies.

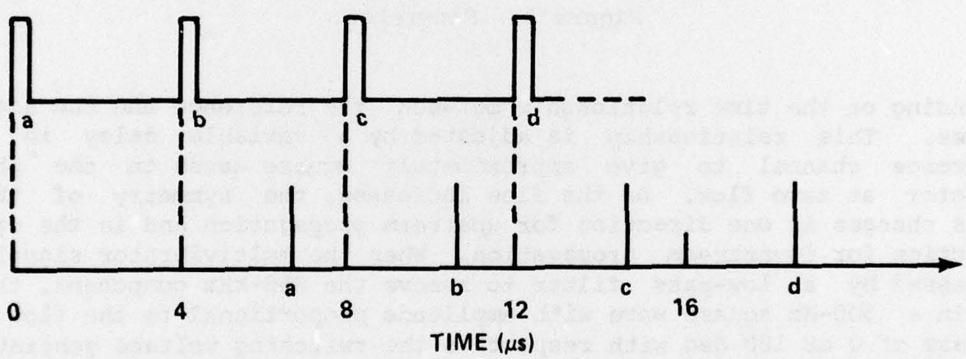

Figure 4. Time relationship between upper transmitted pulses and lower received pulses.

4. BEAMWIDTH AND ALIGNMENT

Frequency components of the acoustic pulses transmitted lie in a band centered around 10 MHz. Disc transducers of 2-mm diameter would then have about 6-deg beamwidth. No attempt has been made to calculate the beam shape for annular discs with the obstructing needles. The shape is expected to be quite narrow, and experience confirms that it is. Hence, the alignment is critical with respect to the signal amplitude; but because of the construction method described, the alignment is easily controlled.

5. SENSITIVITY

The difference in the upstream and downstream transit times is

$$\Delta t = \frac{2dv \cos \theta}{c^2}, \tag{1}$$

where

d is the transducer spacing,

v is the flow velocity,

θ is the angle in figure 1,

c is the acoustic propagation velocity (1.5×10^5 cm/s).

Zero stability corresponds to a flow velocity of 0.1 cm/s. Therefore, if the transducer spacing is 1 cm, because $\cos \theta$ is approximately unity, $\Delta t = 10^{-11}$ s. The necessity for measuring such small time differences requires switching and synchronous detection to eliminate the effects of changes in d or c.

The amplitude, V, of the 500-Hz square wave after the phase detector integrator is

$$V = 10 \frac{\Delta t}{T} \text{ volts peak to peak,} \tag{2}$$

in which $T = 1/PRF = 4$ µs. The factor 10 occurs because the 250-kHz rectangular wave at the phase detector has a 10-V amplitude. Manipulation of equations (1) and (2) shows that with 1-cm transducer spacing, a maximum flow velocity of 4.5×10^4 cm/s can be measured, because the phase meter becomes ambiguous at higher flows.

6. VELOCITY PROFILE AND TURBULENCE

Gessner[4] has discussed the effects of laminar and turbulent flow on the output of an ultrasonic flowmeter whose transducers are mounted externally and for which the sensitive volume between transducers does

[4] *U. R. S. Gessner, The Performance of the Ultrasonic Flowmeter in Complex Velocity Profiles, IEEE Trans. Biomed. Eng.,* BME-16 *(April 1969), 2.*

not cover the entire vessel cross section. He concludes that the net fluid velocity would be overestimated by 33 percent for laminar flow and by 7 percent for turbulent flow and that the performance on the aortic flow would be satisfactory in most cases. Gessner does not discuss the effects of a flow profile on a catheter-tip probe, but the flow instability leading to turbulence is undoubtedly increased by the presence of the probe.

7. EXPERIMENTAL RESULTS

The flowmeter was calibrated with the catheter probe inserted in a 3/8-in. (0.95-cm) i.d. Tygon tube with water flows up to about 40 cm/s. At zero flow, the stability of the flowmeter was 0.1 cm/s, and transducer connections to the chassis could be interchanged without changing the zero reading more than that amount. This procedure allows zero to be established during an animal experiment without stopping the flow, because the procedure creates a reflection of the pulse waveform about the zero line.

Figures 5 and 6 were recorded during the same animal experiment at the Washington Hospital Center, Washington, DC. They show typical curves of flow in the aorta and in the abdominal aorta, respectively.

Figures 7 and 8 were recorded at Georgetown University. They both show flow in the abdominal aorta at the beginning and end of an experiment in which the heart rate was decreased by electrical pulses applied to the animal's neck. (Three heartbeats at the slowed rate in figure 8 are deleted because of space limitations.) The pressure was recorded simultaneously with a separate catheter. In the long intervals between heartbeats, the flow was not zero, but erratic, probably because of mild muscular convulsions which were observed.

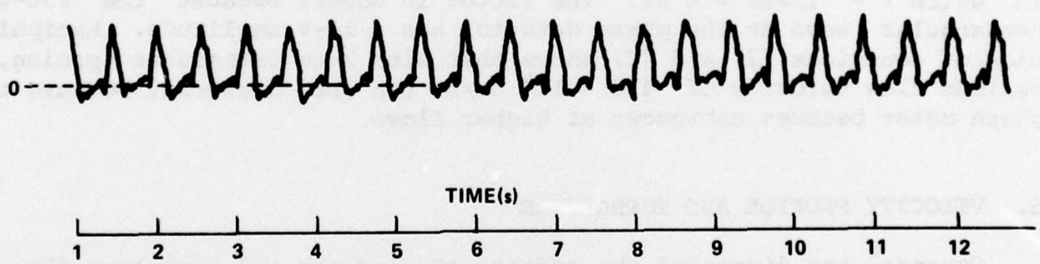

Figure 5. Flow in aorta of animal at Washington Hospital Center.

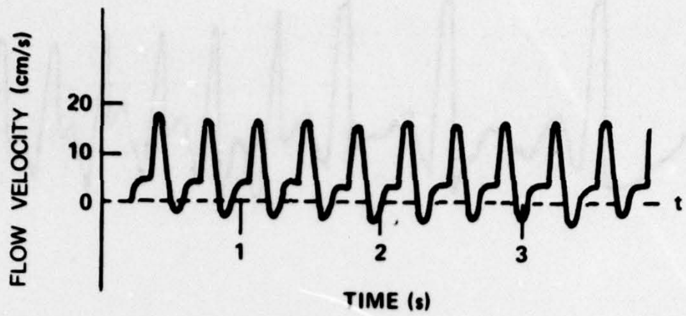

Figure 6. Flow in abdominal aorta of animal at Washington Hospital Center.

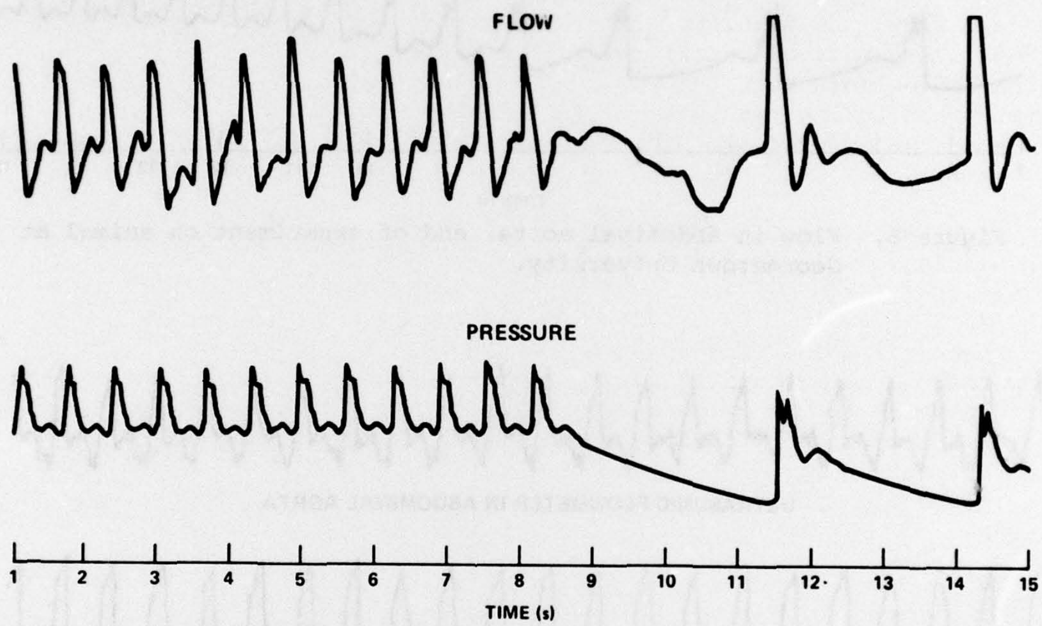

Figure 7. Flow in abdominal aorta, beginning of experiment on animal at Georgetown University.

Figures 9 and 10 were made during another animal experiment at Georgetown University, in which the ultrasonic flowmeter was used simultaneously with a cuff electromagnetic flowmeter, and blood pressure also was recorded. The cuff was on the thoracic aorta in both cases, while the catheter was moved from the abdominal aorta (fig. 9) to the thoracic aorta (fig. 10).

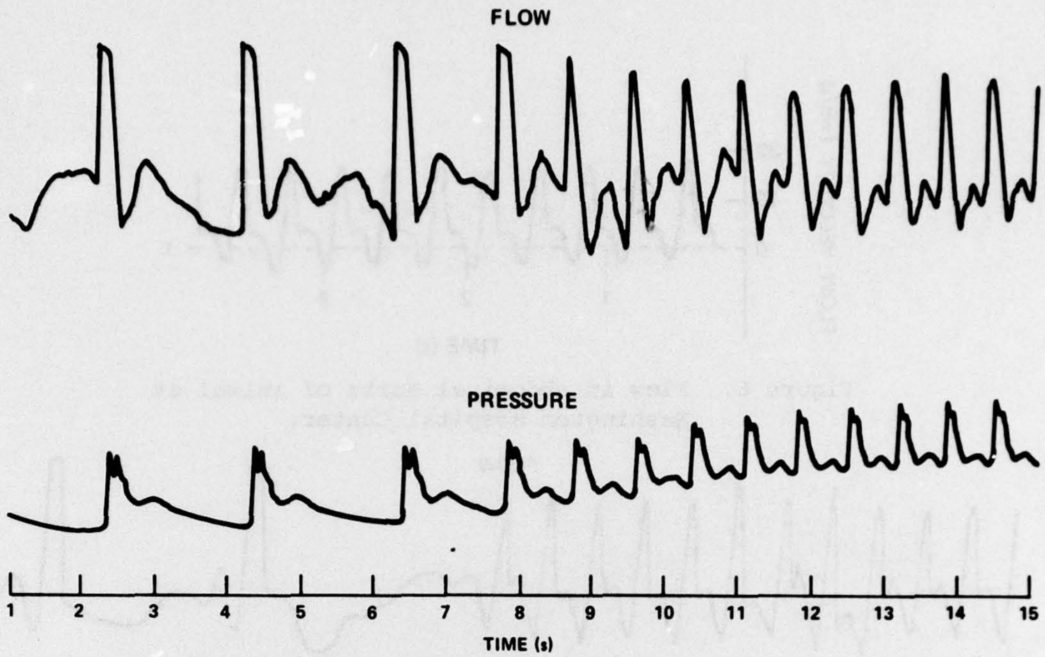

Figure 8. Flow in abdominal aorta, end of experiment on animal at Georgetown University.

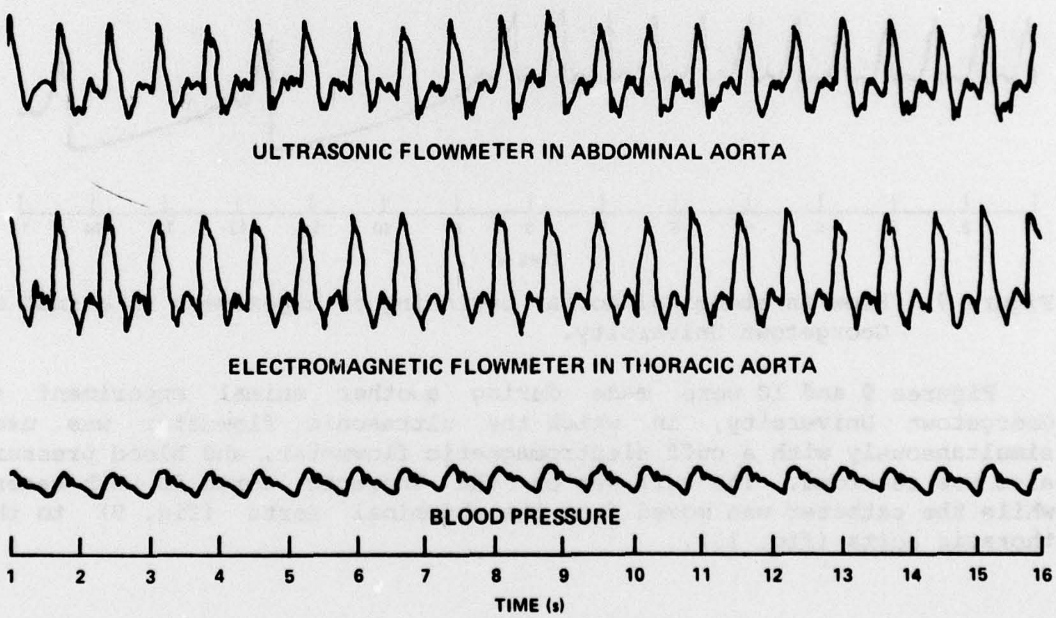

Figure 9. Blood flow and pressure of animal at Georgetown University, catheter in abdominal aorta.

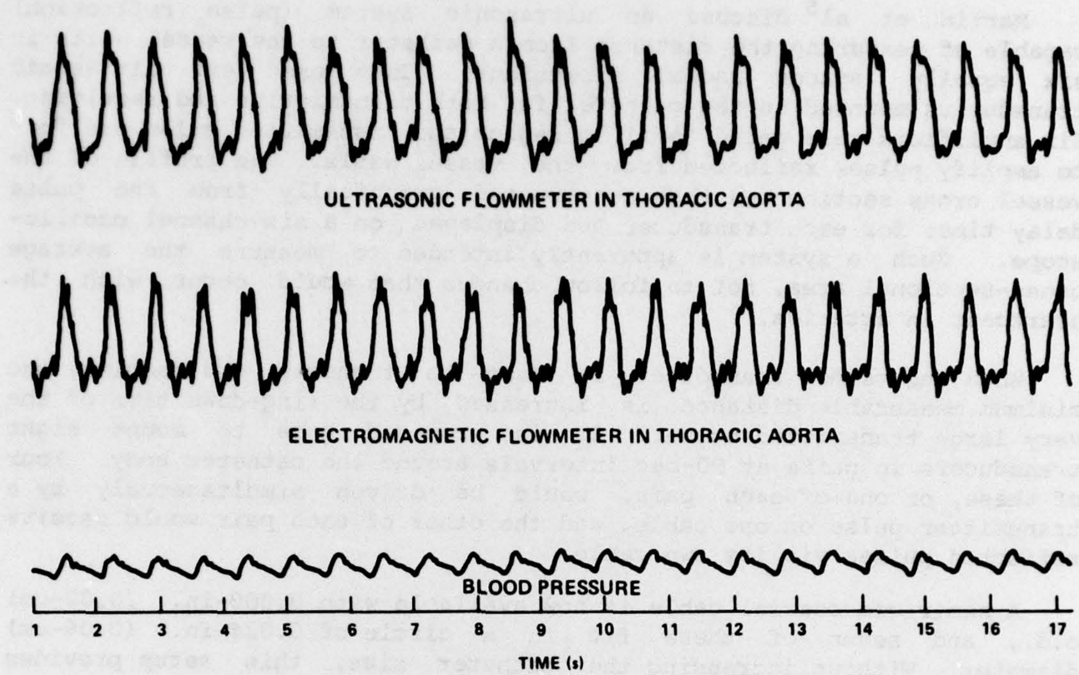

Figure 10. Blood flow and pressure of animal at Georgetown University, catheter in thoracic aorta.

8. CROSS-SECTION MEASUREMENT

At present, this flowmeter develops an output proportional to the flow velocity, but in many cases the flow volume is desired. If another measurement can be made with an analog voltage output proportional to the vessel cross-sectional area, A, and this voltage and flowmeter output are the two inputs to an integrated-circuit multiplier, then the multiplier output is

$$kV = kvA ,$$

where

k is a constant that can be determined experimentally,

V is volume flow,

v is flow velocity.

Martin et al[5] discuss an ultrasonic system (pulse reflection) capable of measuring the distance from a catheter to the vessel walls in six equally spaced radial directions. They used six ultrasonic transducers mounted on the catheter for both transmitting and receiving. Six amplifiers were gated "off" to reject the transmitted pulse and "on" to amplify pulses reflected from the vessel walls. The profile of the vessel cross section was then constructed graphically from the pulse delay times for each transducer and displayed on a six-channel oscilloscope. Such a system is apparently intended to measure the average cross-sectional area, not to follow changes that would occur with the heartbeat in arteries.

When the same transducer is used to transmit and receive, the minimum measurable distance is increased by the ring-down time of the very large transmitted pulse. It is proposed here to mount eight transducers in pairs at 90-deg intervals around the catheter body. Four of these, or one of each pair, would be driven simultaneously by a transmitter pulse on one cable, and the other of each pair would receive reflected pulses via its own cable.

A semirigid coaxial cable is now available with 0.008-in. (0.02-cm) o.d., and seven of these fit in a circle of 0.024-in. (0.06-cm) diameter. Without increasing the catheter size, this setup provides five shielded cables for measurement of the cross section and the two cables required to measure flow velocity. Separate transducers for transmitting and receiving permit measurement of cross section in smaller vessels. An appropriate transducer beamwidth of ±6 deg can be achieved for 10-MHz pulses with transducers 1 mm in diameter.

If the transmitted pulse is applied to one input of a bistable multivibrator, and if the received, reflected pulse is applied to the other input, the multivibrator develops a voltage proportional to the delay time, or the distance to the vessel wall reflection. This signal repeats after a delay time or distance corresponding to 1/PRF, which sets an upper limit of PRF = 25 kHz for a maximum range of 3 cm without ambiguity. This PRF is adequate to follow changes occurring with the heartbeat.

The optimum signal processing scheme to convert four distinct range measurements to a voltage proportional to the cross section is not yet known, but that does not appear to be a difficult problem. A particular scheme can be evaluated by moving the catheter tip to positions of different areas in a tube with a constant volume flow.

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[5] *R. W. Martin, L. E. Lindbloom, and G. H. Pollack, Ultrasonic Catheter Tip Instrument for Measurement of Vessel Cross Sectional Area, 27th ACEMB, Philadelphia, PA (October 10, 1974).*

A pair of transducers was mounted on a catheter and moved from the abdominal aorta to the aortic arch in one animal experiment. The signal-to-noise ratio was adequate for measurement of the vessel size at all points.

9. CONCLUSIONS

Considerable progress has been made recently in constructing catheters. Their fabrication is much more easily controlled than that of earlier versions, and the recent ones are both smaller and more rugged. By use of the present design, their size can be reduced further with little increased difficulty.

When measurements are made at points in the aorta and then the catheter is moved and returned to the same point, the results are consistent. Therefore, it is believed that little difficulty is caused by uncertainty about the tip orientation in the vessel.

When transducers are included close to the tip for diameter measurement, they also will provide information about the orientation.

ACKNOWLEDGEMENT

The authors thank Karel B. Absolon and Elias Dergal of the Washington Hospital Center and John C. Rose and Peter H. Kot of Georgetown University for performing the animal experiments to evaluate this flowmeter.

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